

# Comparison of Damaged Borosilicate Constitutive Constants Obtained with Confined-Compression and Constant-Pressure-Compression Devices

(Comparison of “sleeve” and “bomb” tests)



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# Objectives

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- Ultimate objective: Transfer properties measured in the lab to ballistic simulations that can predict ballistic tests results
- Milestones:
  - Determine with laboratory experiments the strength of damaged borosilicate and soda-lime at low and high confining pressures
  - Find the Drucker-Prager constants,  $\beta$  and  $Y_0$ , in an independent way and compare them with the sleeve tests.
  - Validate sleeve tests



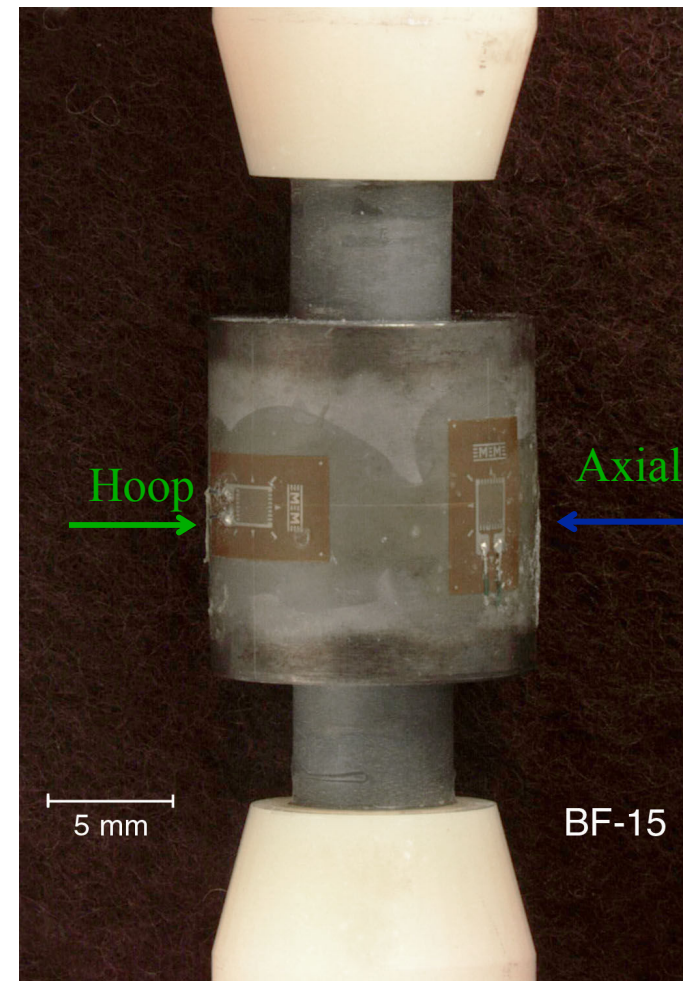
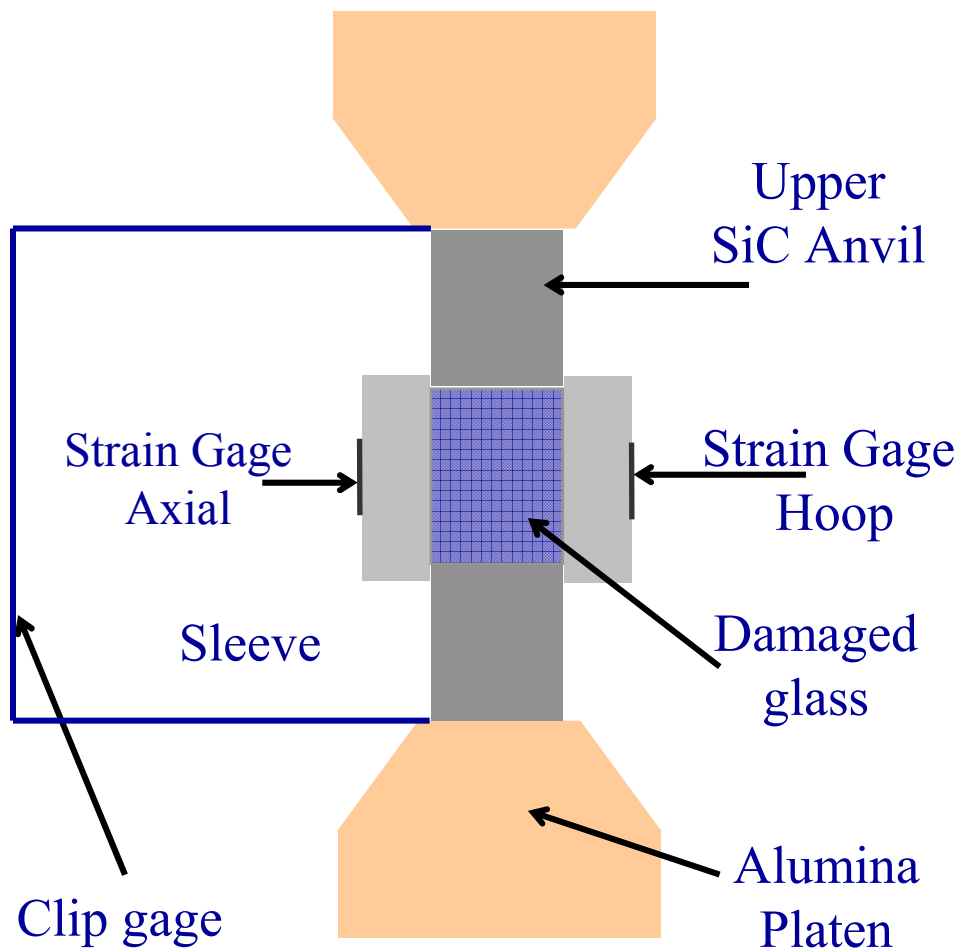
## Damaged Borosilicate Glass

- Two cycles in oven at 500 C and iced water.
- Structural integrity
- Why damaged borosilicate?
  - During ballistic penetration the projectile is in direct contact with damaged material.



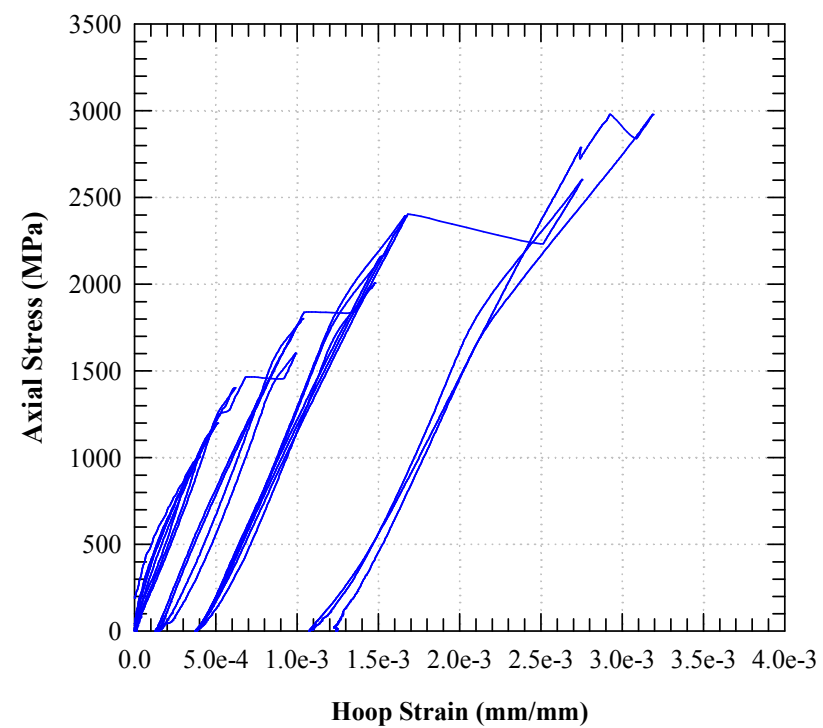
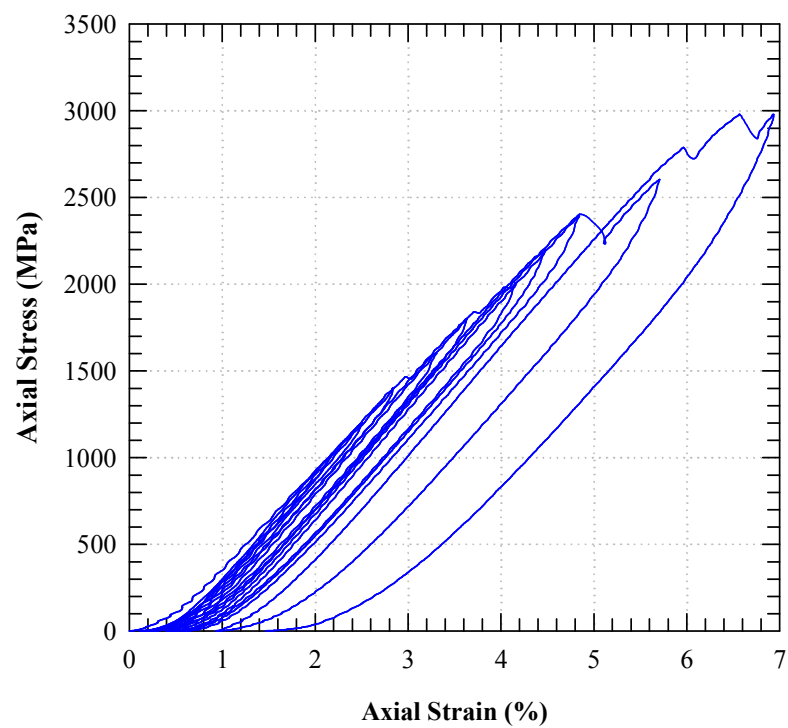


## Review: “Sleeve” test set-up



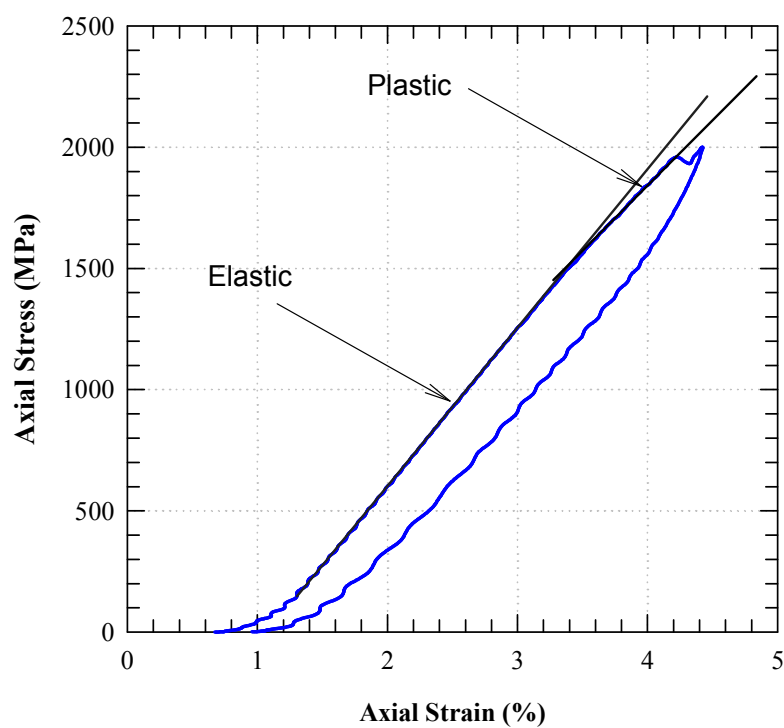


## Review: “Sleeve” test results

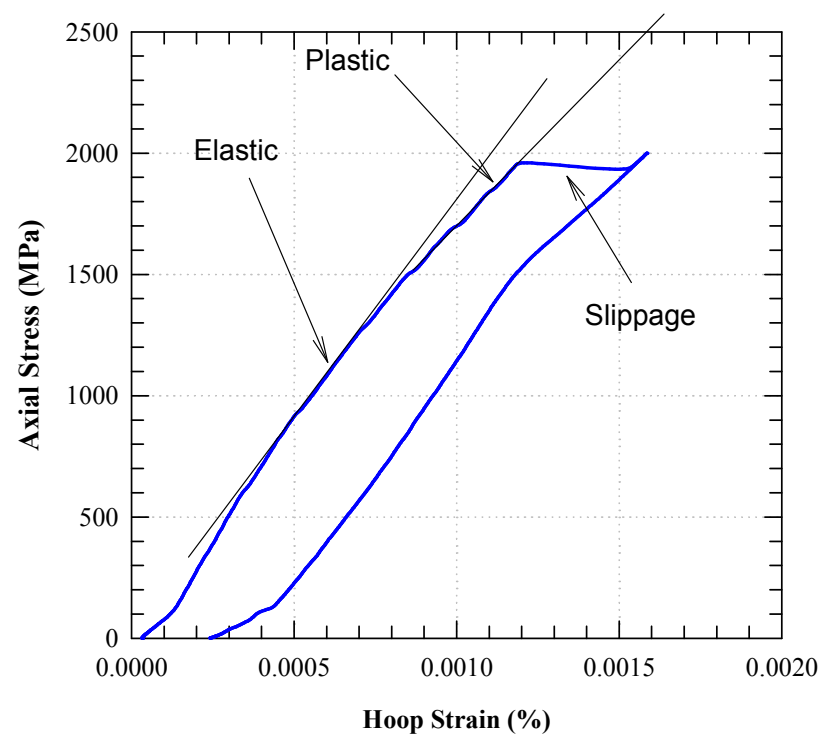




## Review: “Sleeve” test results



bf23-cycle4

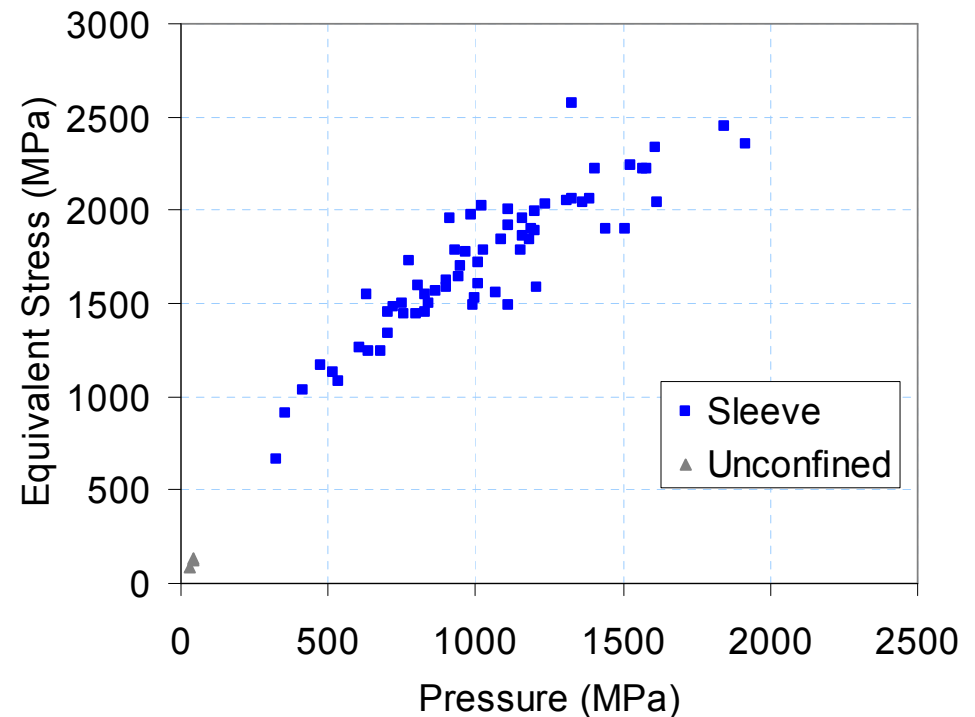


bf23-cycle4



## Review: “Sleeve” test results

- Assumed Drucker-Prager
$$Y = Y_0 + \beta P$$
- Analysis of sleeve data
$$\beta = 1.8$$
- Analysis of unconfined data
$$Y_0 = 43 \text{ MPa}$$

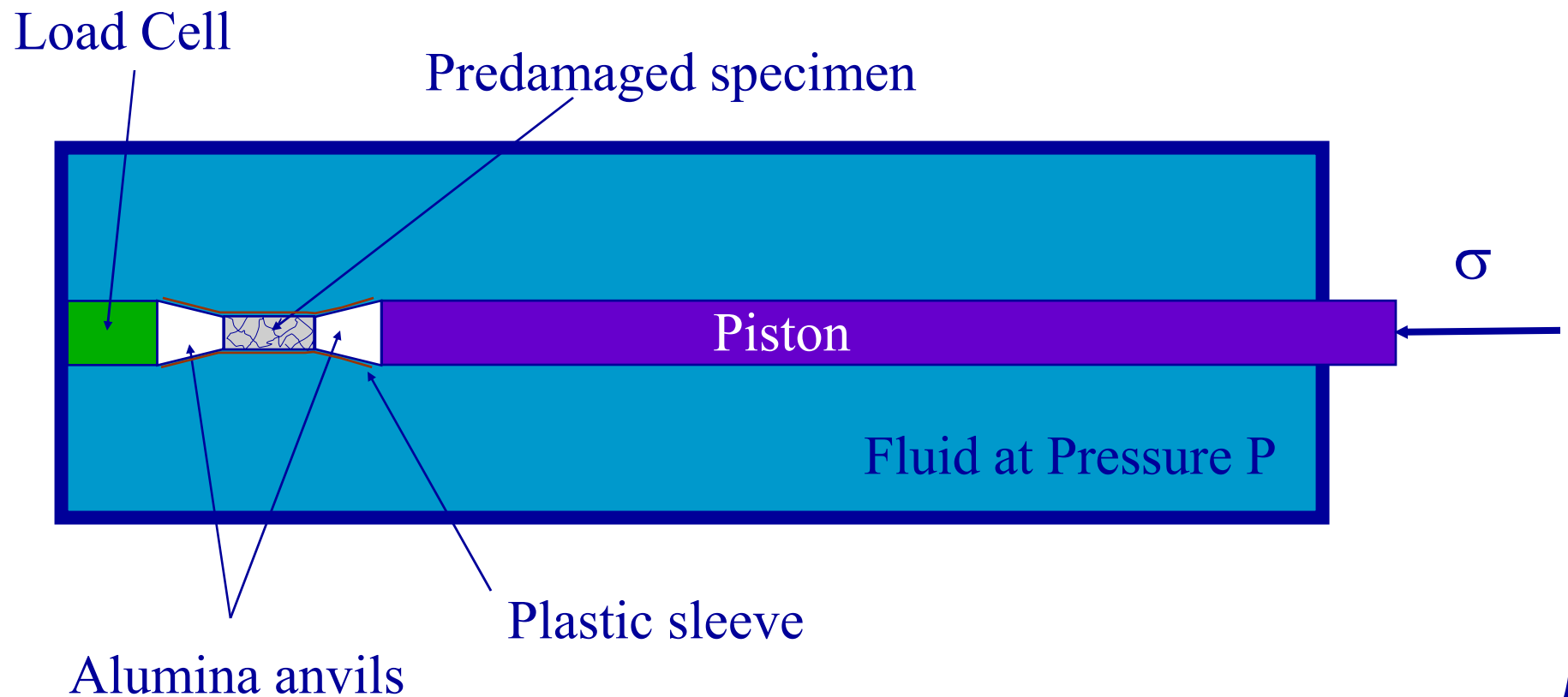


Data from 13 different tests.  
Each test can provide more than one point  
because of load/reload cycles



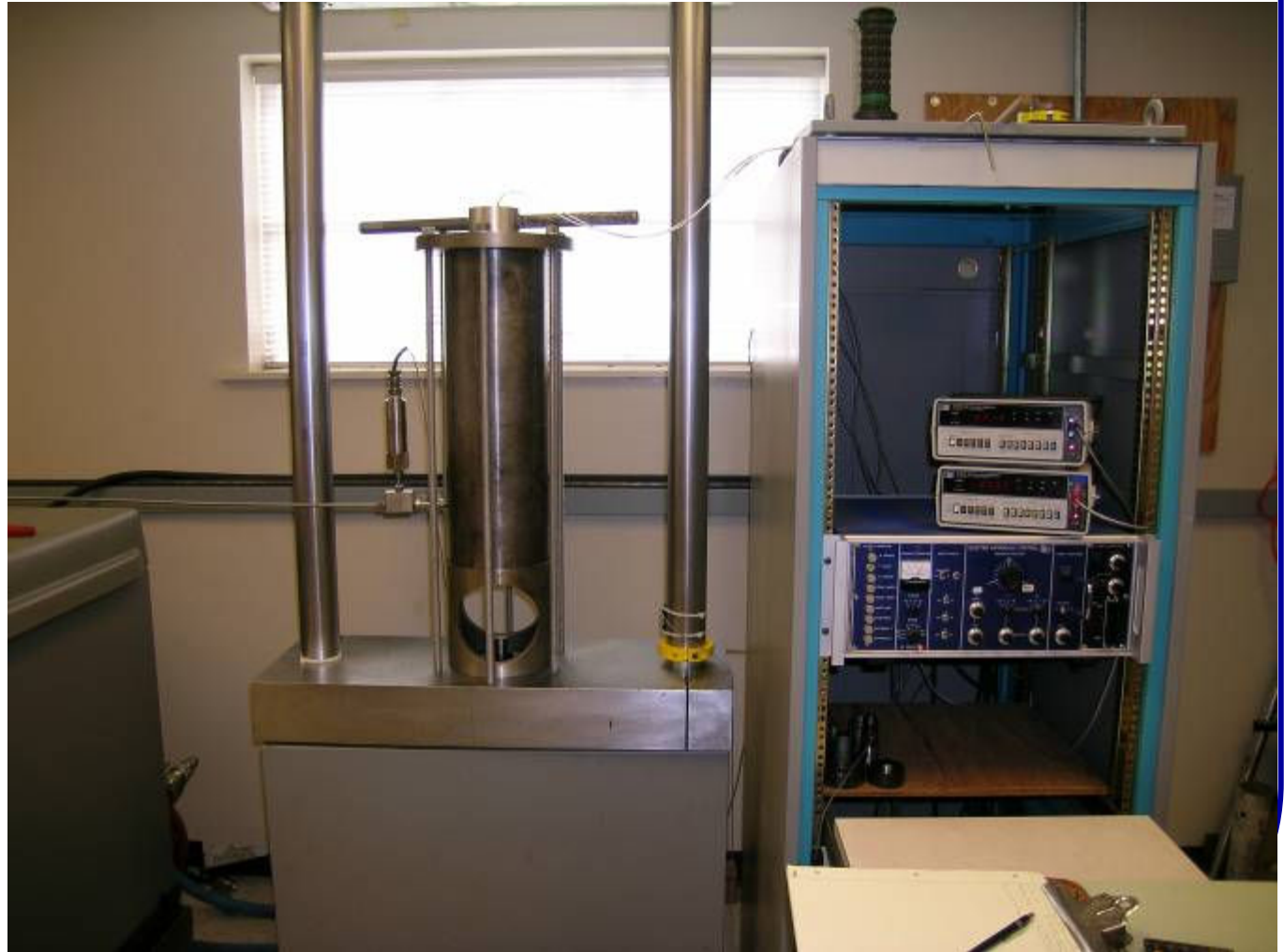


## Setup of bomb test

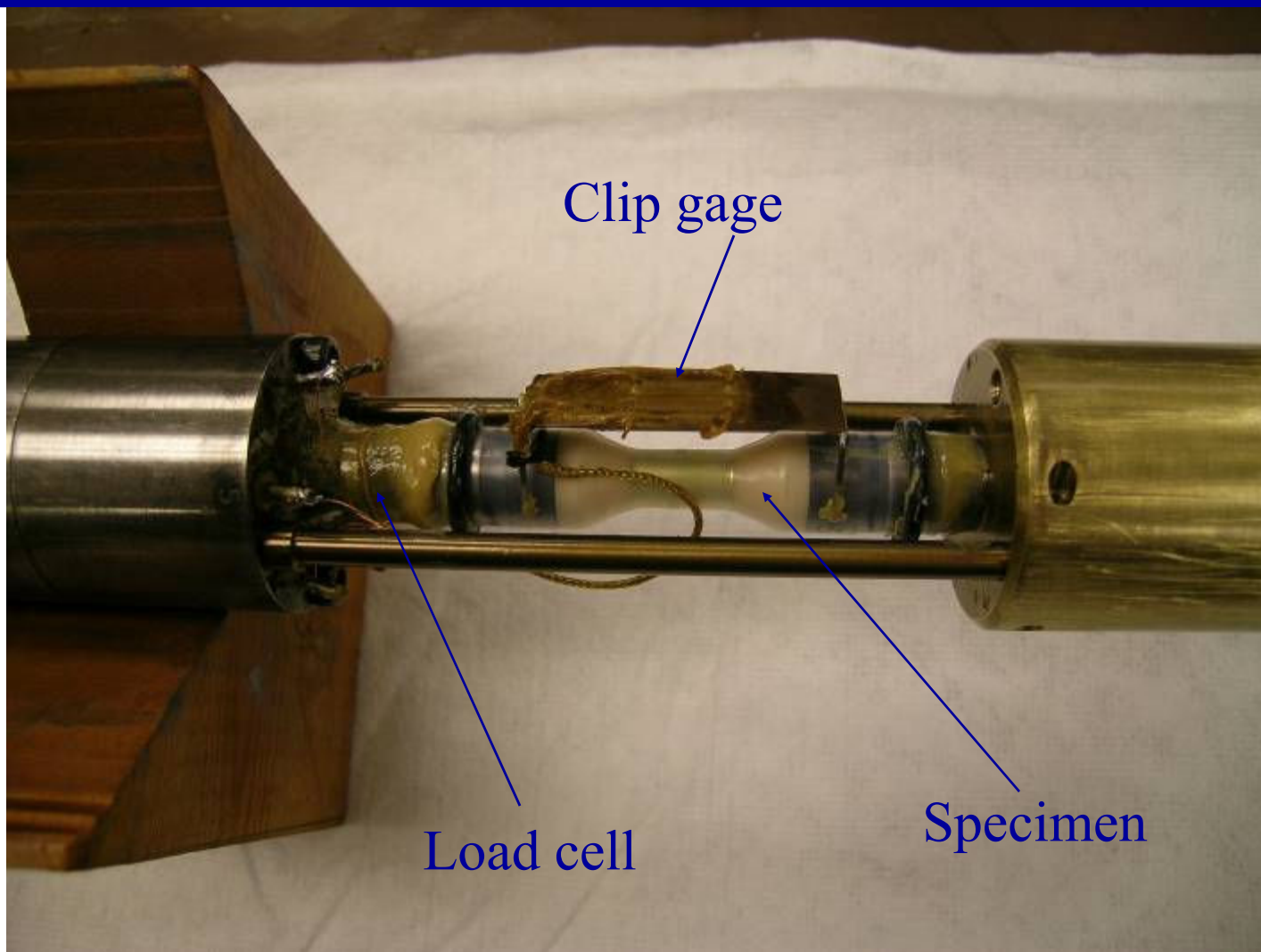




OD = 7.5 in  
ID = 1.5 in  
Thick = 2.5 in  
Length = 23 in

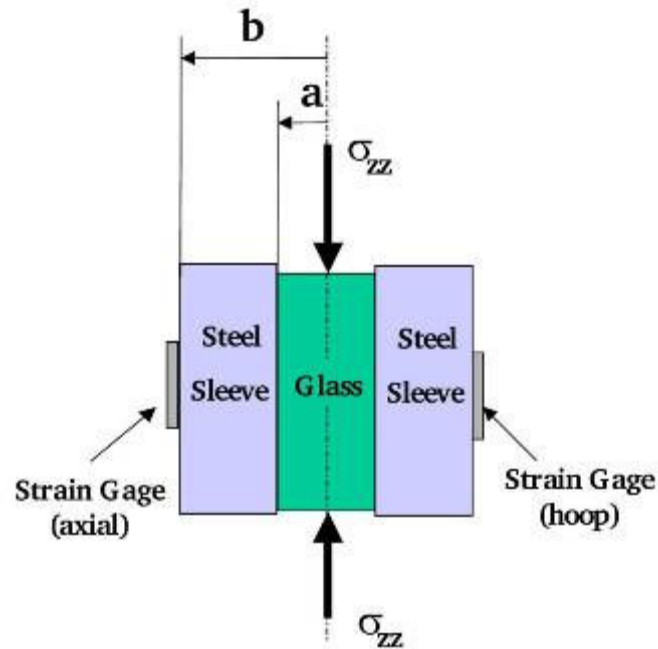






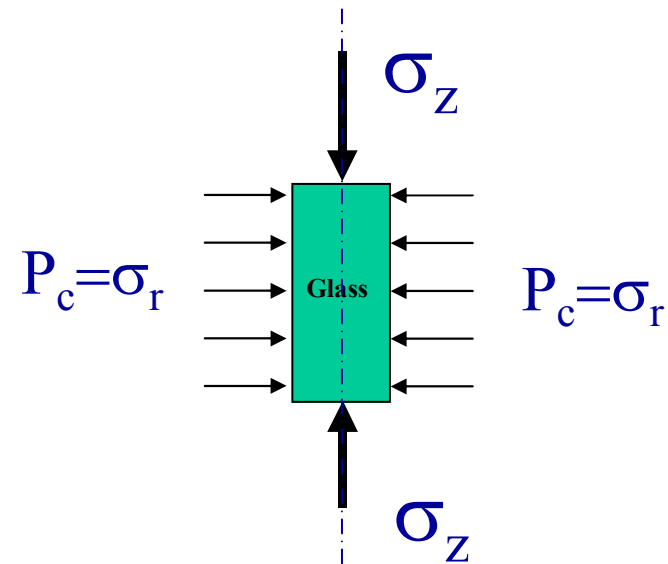


# Comparison of test methods



## Sleeve Test

- Confinement pressure changes during the test
- The analysis is involved
- An analytical model is needed to infer constants
- Conceptually more involved but test relatively straightforward in practice.

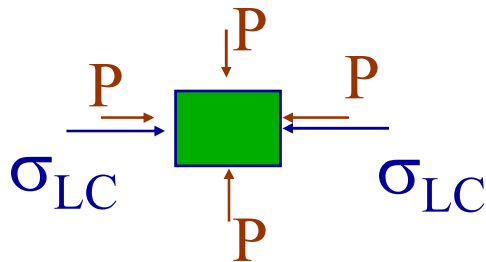


## Bomb Test

- The confinement pressure is kept constant during the test
- Conceptually easy test, difficult in practice



## Bomb test technique

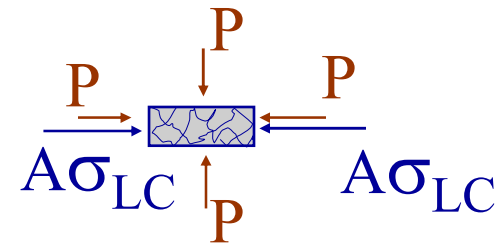


$\sigma_{LC}$  is the output given by the load cell. Strain gages on load cell are mounted to directly give the equivalent stress.

$\sigma_z$  is negative in compression ( $P$  is positive in compression)

$A$  is the area reduction factor between anvil and specimen:

$$A = A_{\text{anvil}} / A_{\text{specimen}}$$



Axial stress on specimen:

$$\sigma_z = A\sigma_{LC} - P$$

Hydrostatic Pressure in specimen:

$$P_H = -\frac{1}{3}(\sigma_z + 2\sigma_r) = -\frac{1}{3}(\sigma_z - 2P)$$

Equivalent stress of specimen:

$$\sigma_{eq} = |\sigma_z - \sigma_r| = |\sigma_z| - P = A|\sigma_{LC}|$$



## Expected “theoretical” results

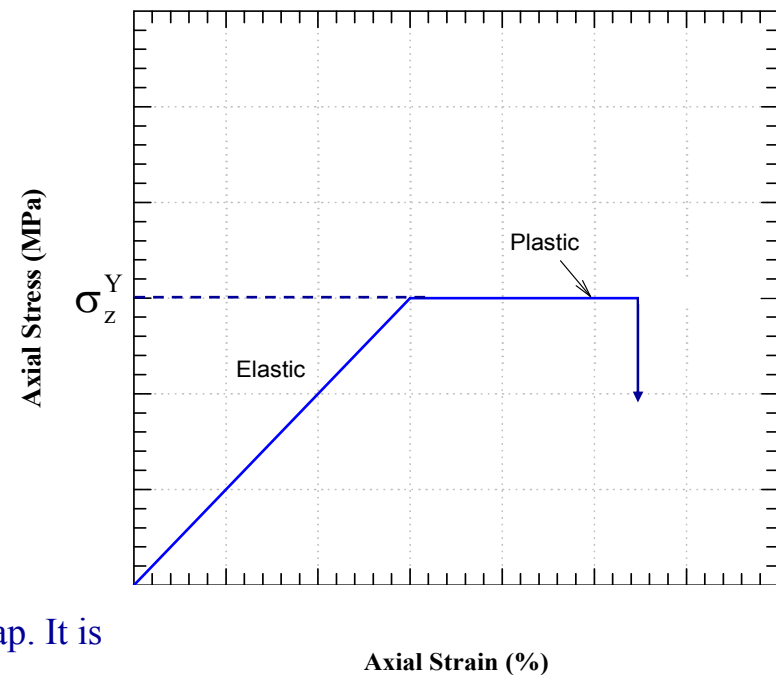
$$\sigma_{eq} = |\sigma_r - \sigma_z|$$

$$\text{Drucker-Prager: } Y = Y_0 + P_H$$

$$\text{When yielding: } \sigma_{eq} = Y \Rightarrow \sigma_r - \sigma_z = Y_0 + \beta P = Y_0 + \frac{\beta}{3}(\sigma_r + \sigma_\theta + \sigma_z)$$

$$\sigma_z \Big|_{\text{yield}} = \frac{Y_0}{\frac{\beta}{3} - 1} + \frac{2\beta + 3}{\beta - 3} P_C^0$$

Where  $P_C^0$  is the confinement pressure (or fluid pressure)

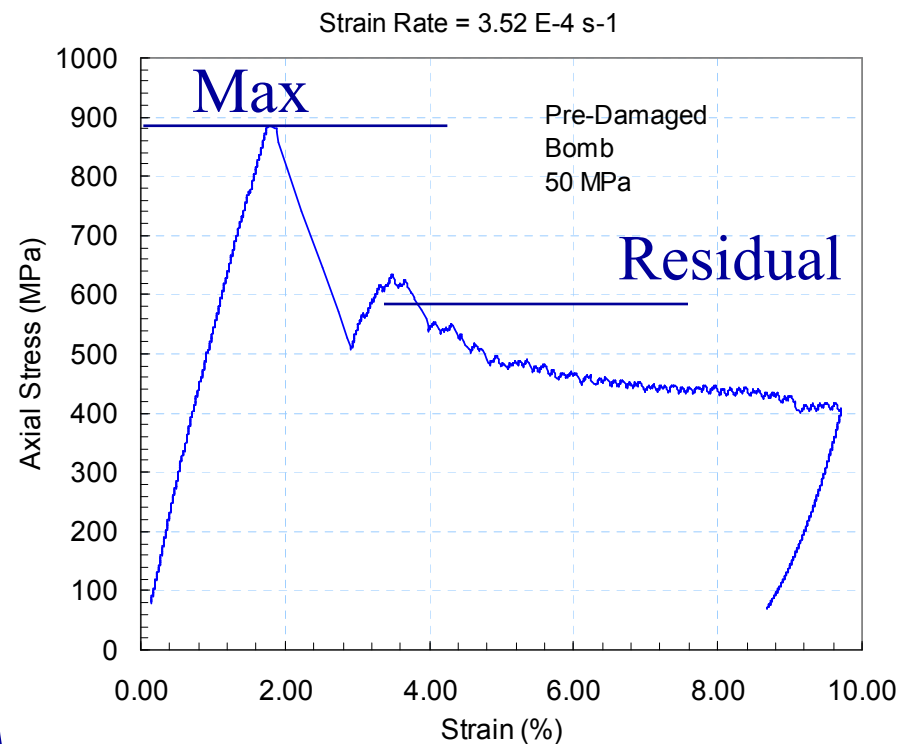


Note: The plateau is NOT a cap. It is “plastic” flow of the sample

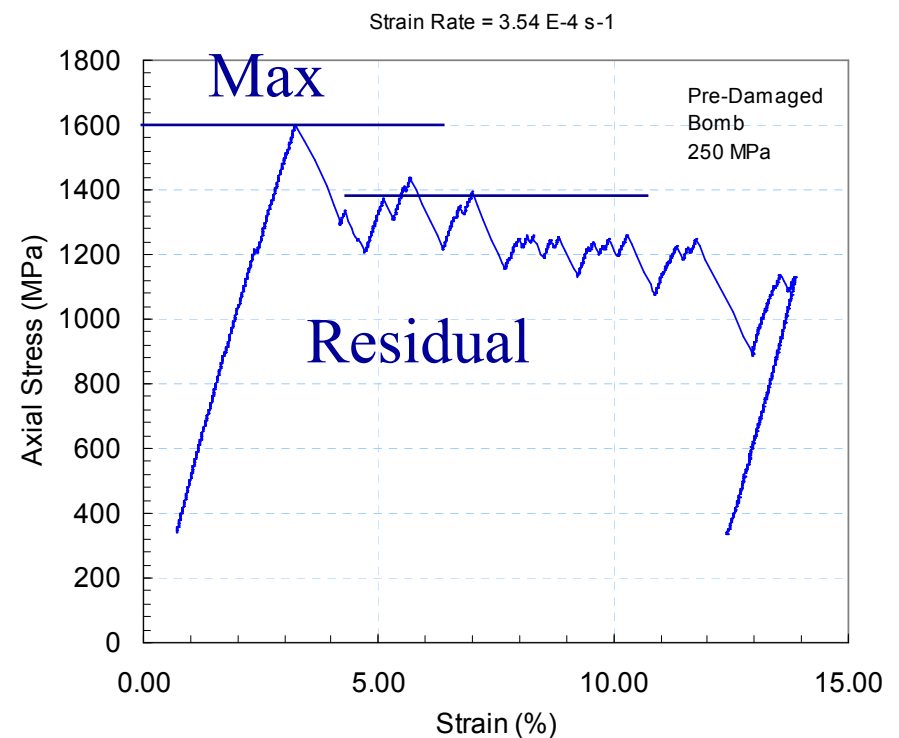


## Example of results (Borosilicate glass)

BF-52



BF-49



The residual strength is created by sliding two faces with friction between them



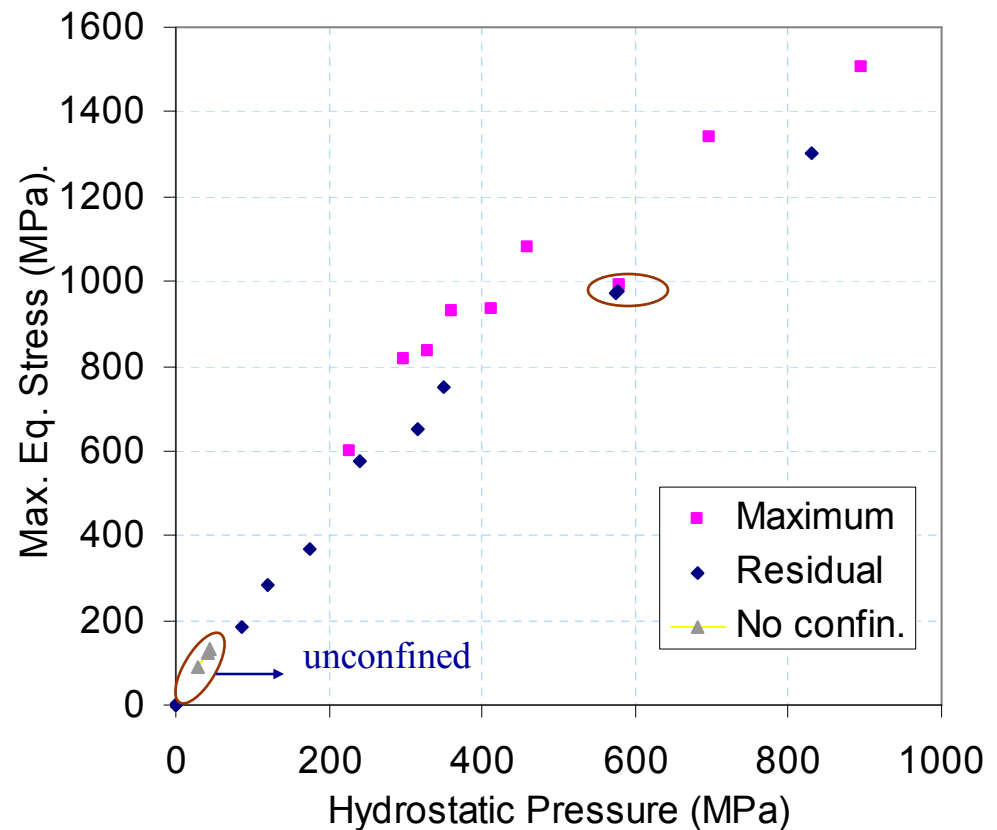


## Max. Equivalent Stress - Borosilicate glass

Each point is a test.  
The triangles are  $P=0$   
(unconfined tests )

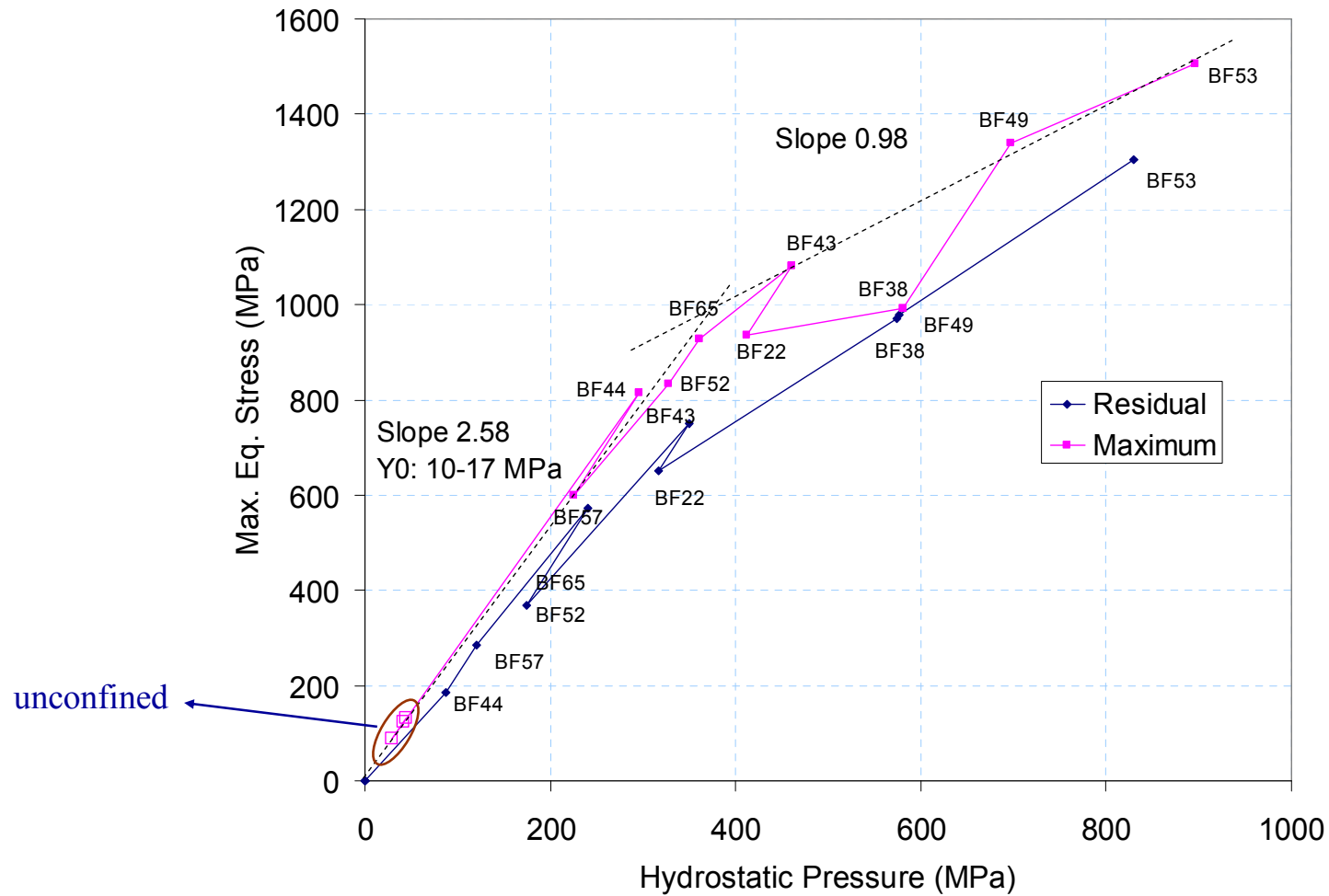
$Y_0$  is around 10 – 20 MPa.

The outlier might have been  
more damaged and directly  
went to the residual curve.



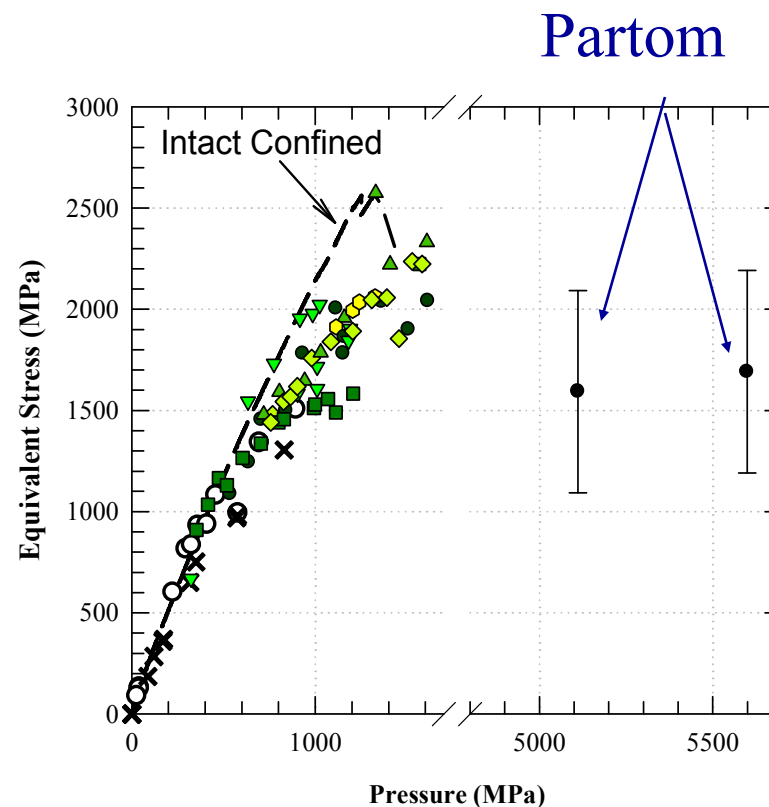
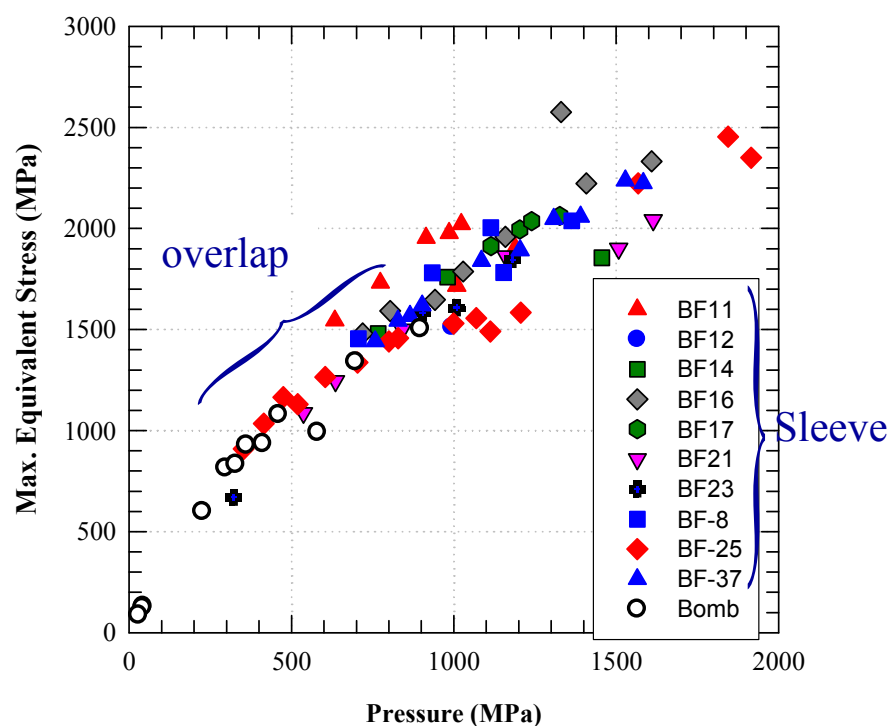


# Max. Equivalent Stress - Borosilicate glass





## Comparison with sleeve data - Borosilicate glass

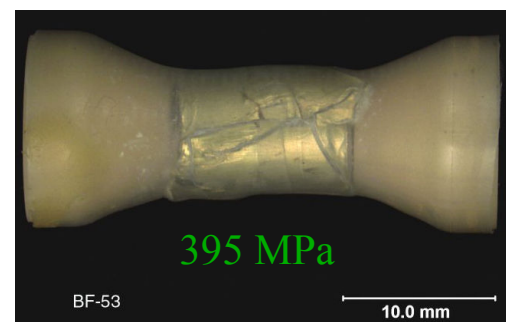
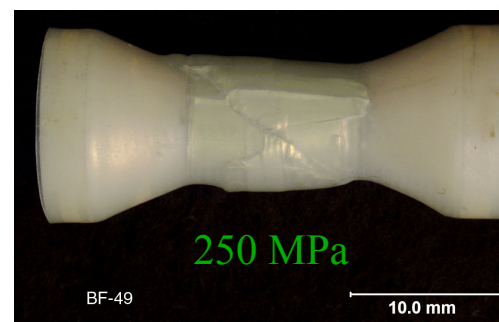
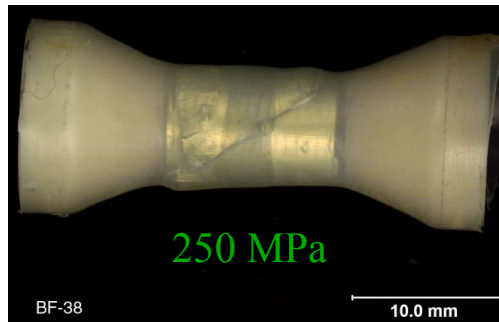
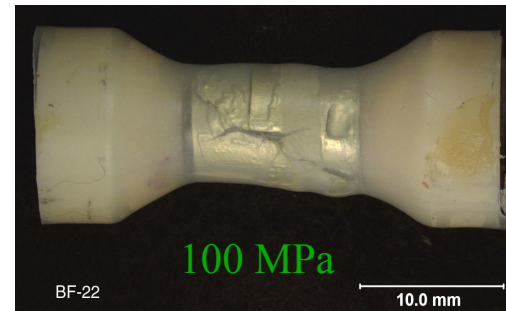
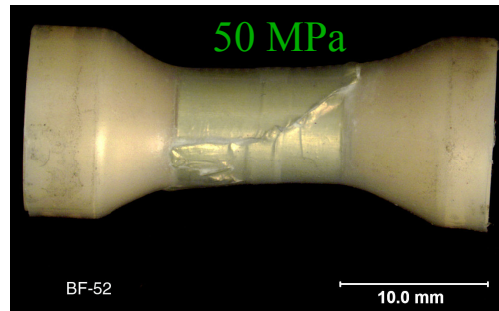
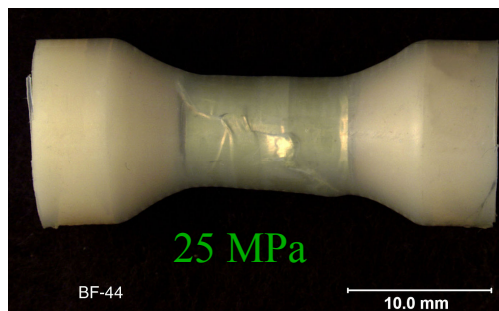


The overlap between sleeve tests and bomb tests gives increased confidence on the sleeve tests results



## Drucker-Prager misses failure pattern

- A Drucker-Prager model is unable to predict a preferred failure angle, something systematically seen in the bomb tests.
- The failure angle does not depend on the fluid pressure (55-65 degs)





# Mohr-Coulomb theory

- Based on maximum shear stress
- Yielding if:  

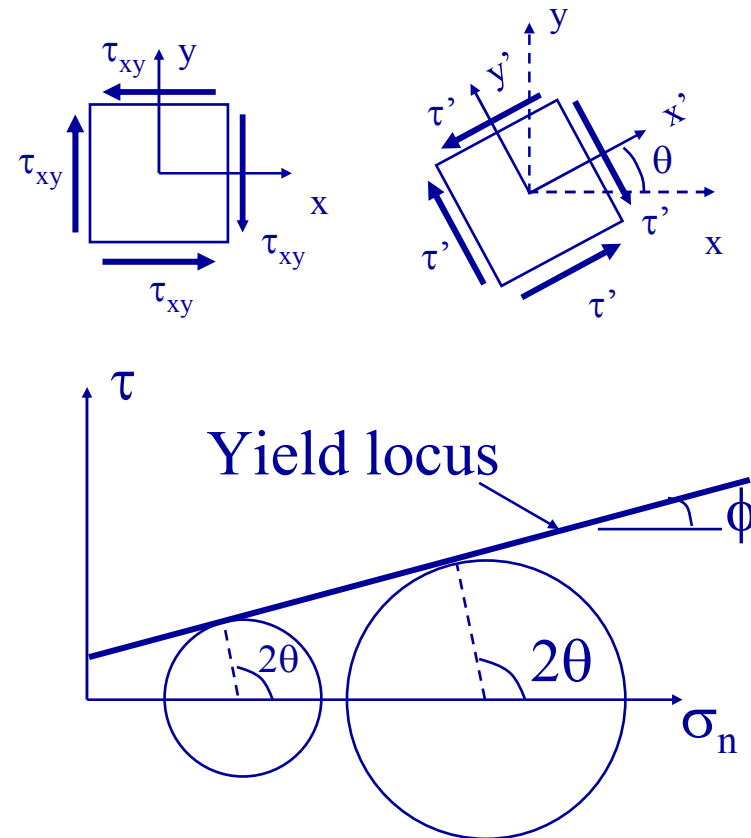
$$\tau = c + \mu \sigma_n$$

$$\mu \text{ is internal friction coeff.}$$

$$c \text{ is cohesion}$$
- For a given stress state the radius and center of the MC circle are:  

$$R = (\sigma_1 - \sigma_3)/2$$

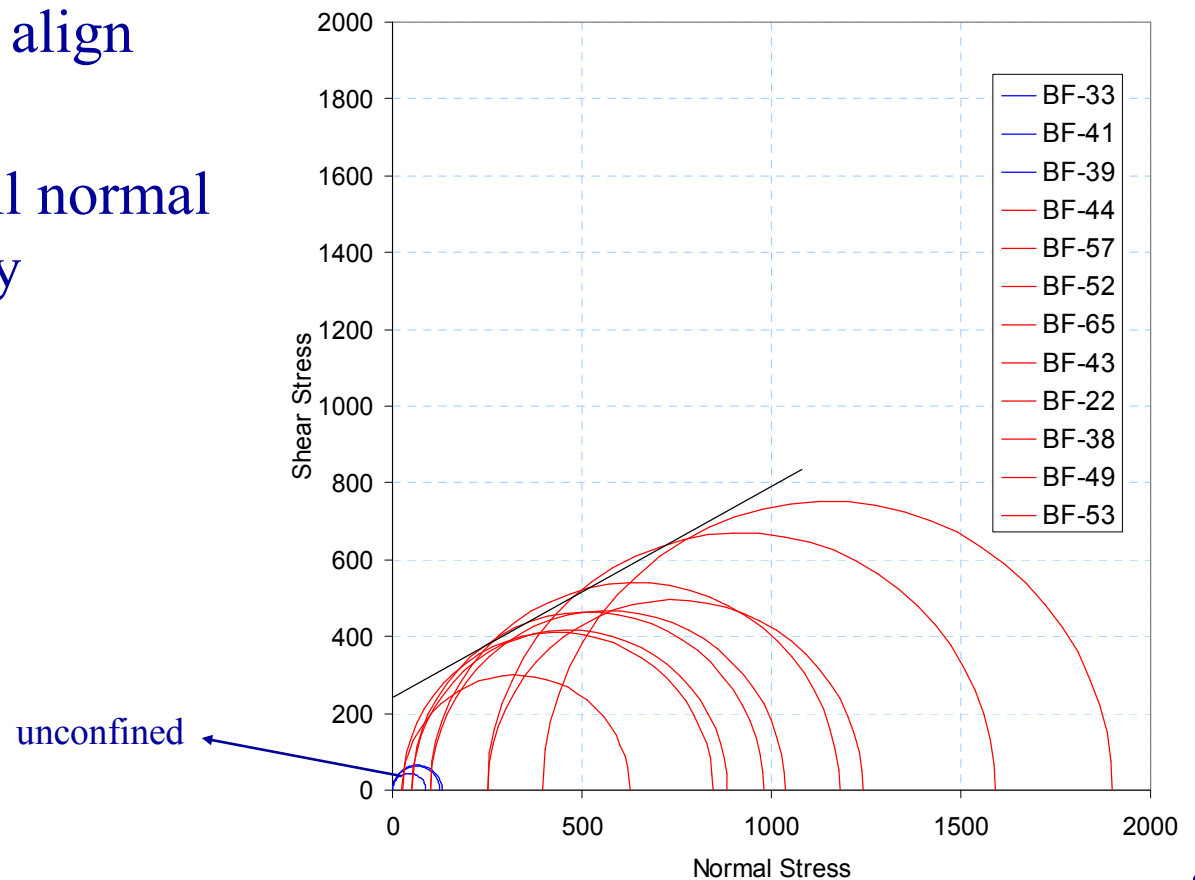
$$C = (\sigma_1 + \sigma_3)/2$$
- Only two tests needed to find the constants





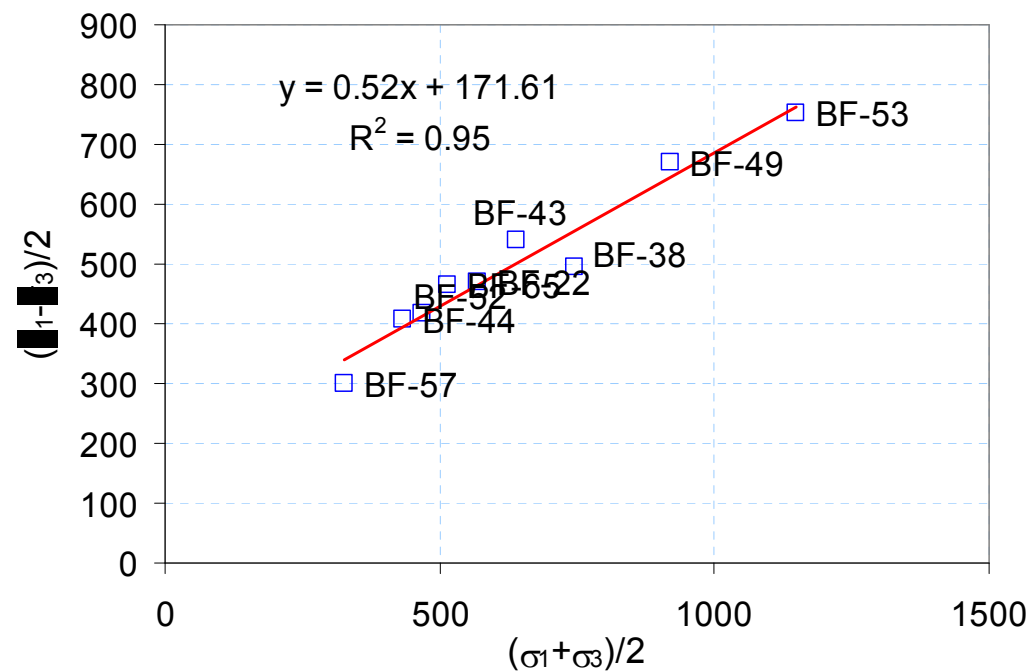
## Bomb tests – MC perspective

- Bomb tests seem to align reasonably well
- Sharp drop for small normal stresses indicated by unconfined tests.





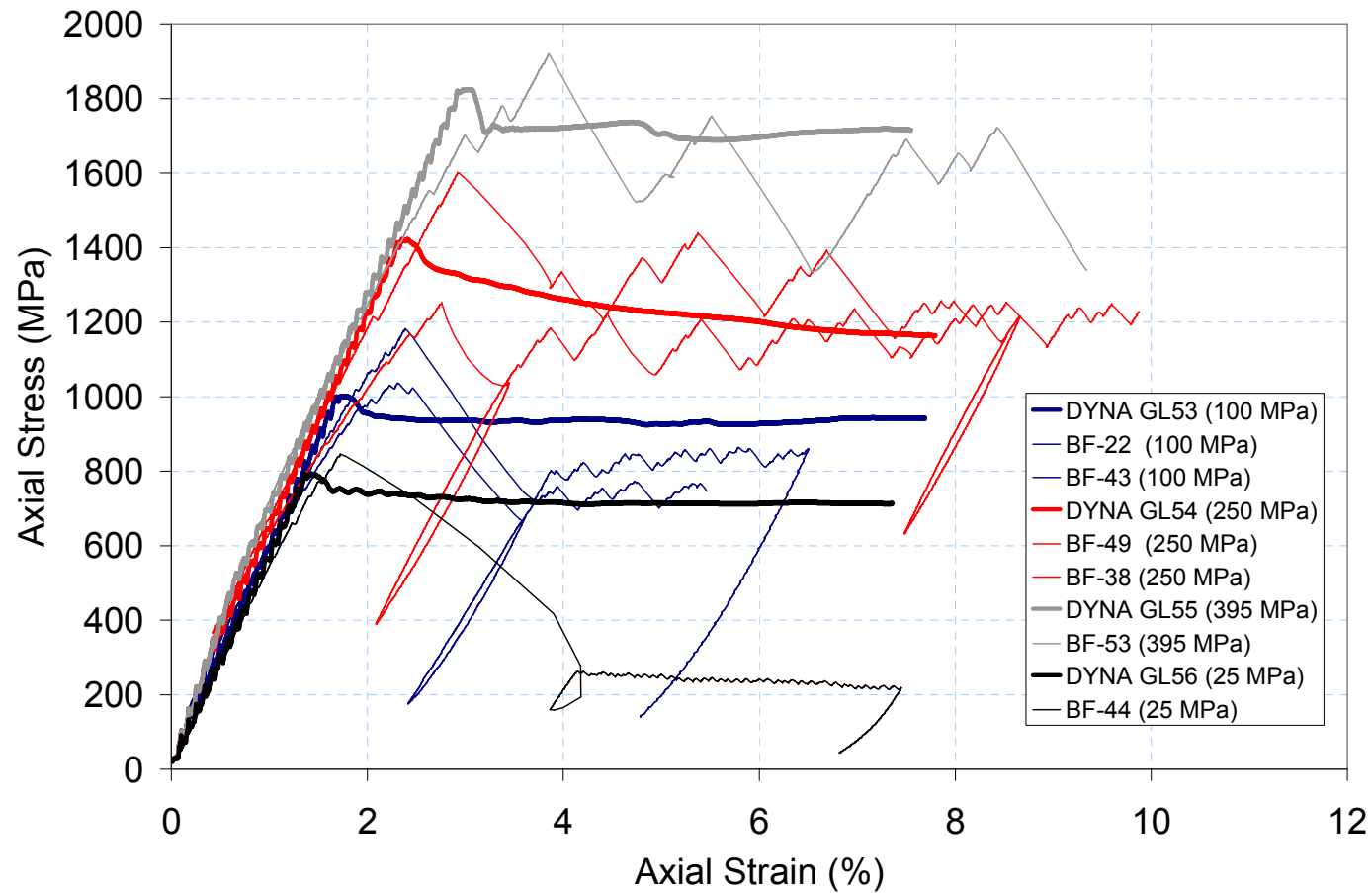
# Bomb – MC parameters



slope	intercept	Angle of friction (deg/rad)	$\mu$	Cohesion (MPa)
0.52	171.61	31.04/0.54	0.60	200.30



## Bomb Tests – LSDYNA simulations with Mohr-Coulomb

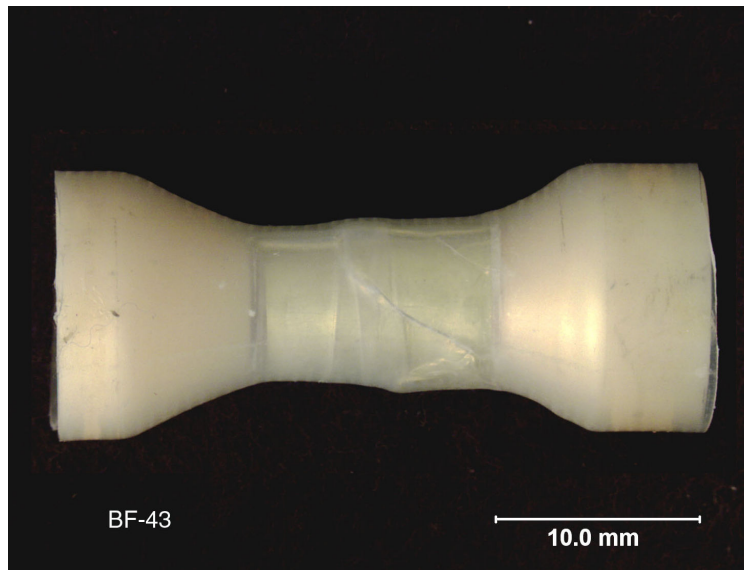


$$\phi=0.51 \text{ rad } (\mu=\tan(\phi)=0.56), c=219 \text{ MPa}$$

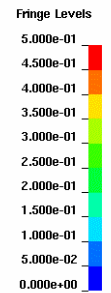
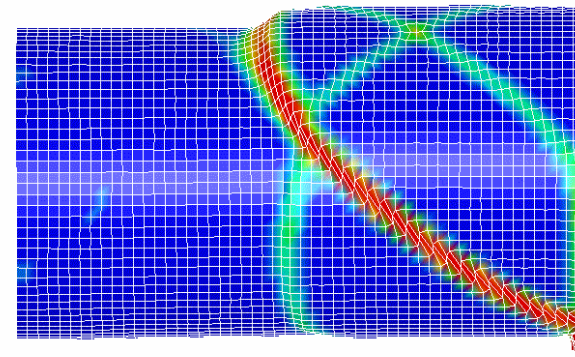




# LS-DYNA Failure Patterns

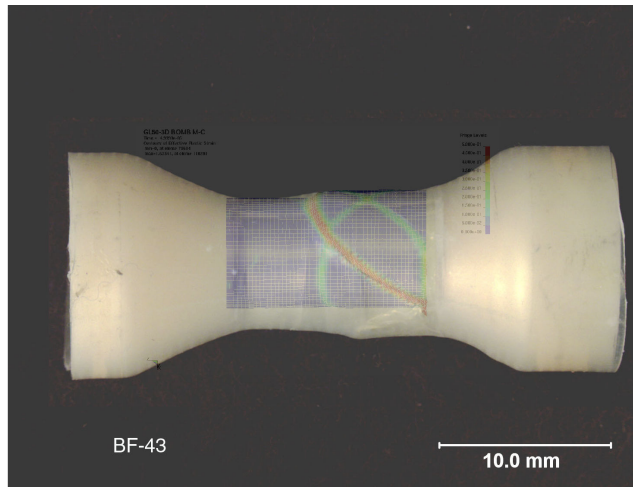


**GL50-3D BOMB M-C**  
Time = 4.39980e-05  
Contours of Effective Plastic Strain  
min=0, at elem# 79694  
max=1.63341, at elem# 110291

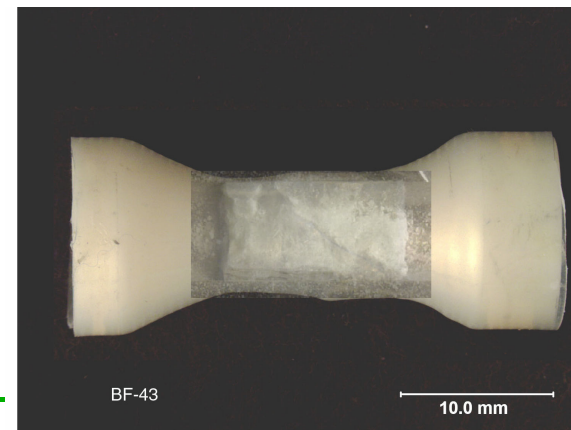




# LS-DYNA Failure Patterns

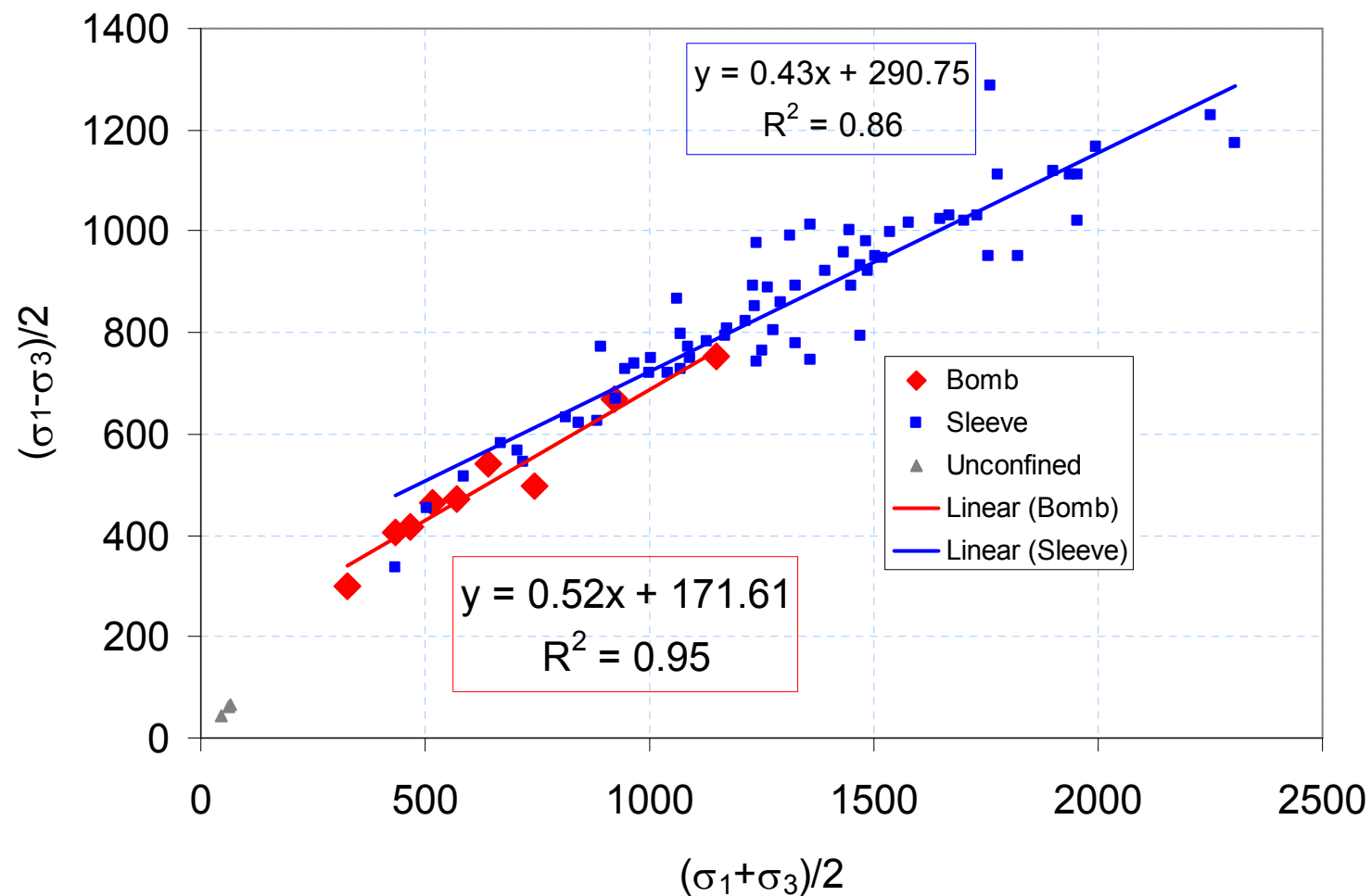


BF-



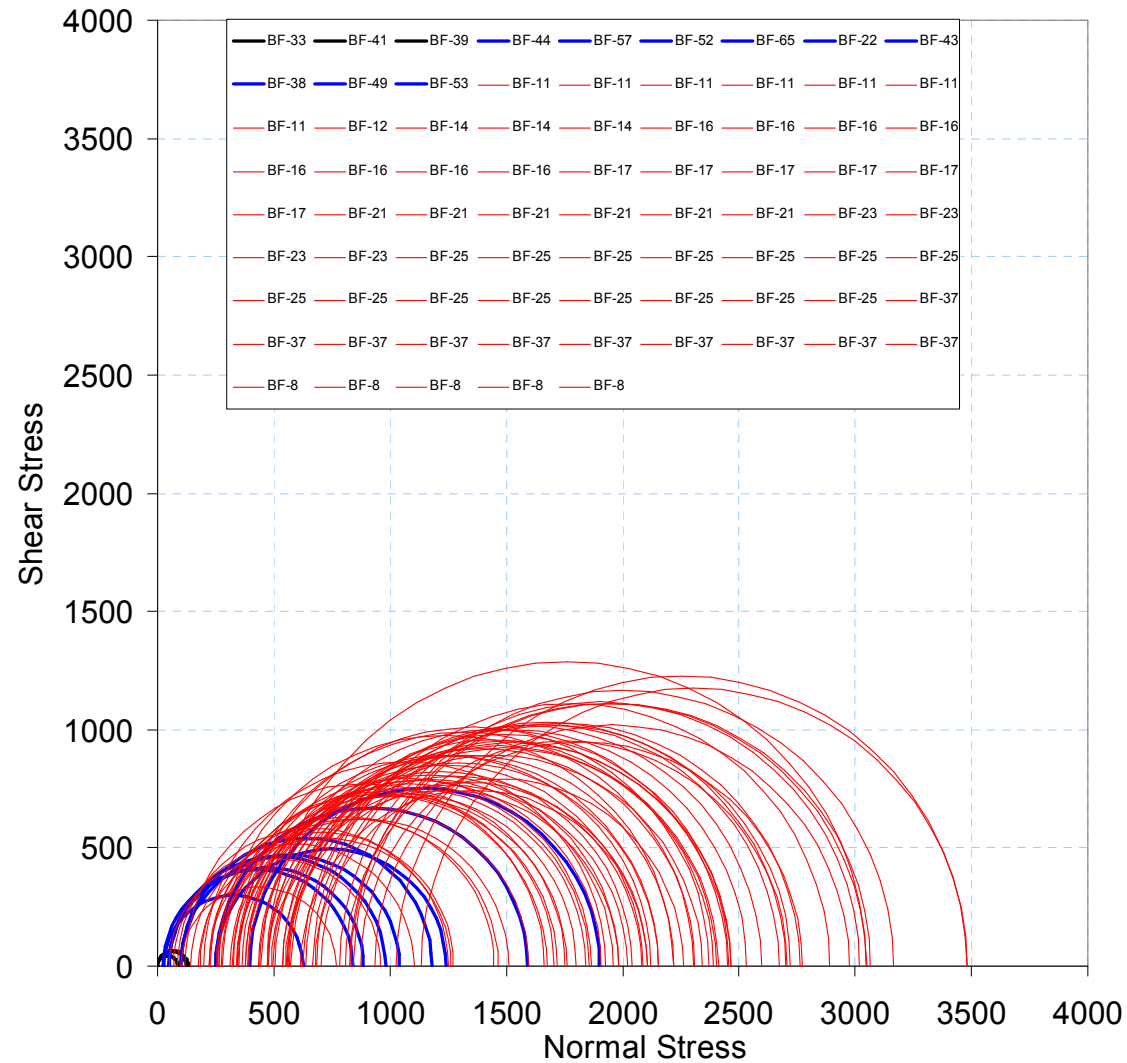


## Sleeve tests from MC perspective





# All the tests





## Conclusions

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- Mohr-Coulomb captures very nicely both strength and failure phenomenon for bomb tests.
- MC also captures failure angle and strength in the sleeve tests.
- The overlap between bomb and sleeve tests support the results of the sleeve tests
- MC is being implemented in CTH to reproduce penetration experiments.



# Acknowledgments

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- To Doug Templeton from TARDEC/RDECOM